

# Average Elemental and Isotopic Composition of Small Solar Energetic Particle Events

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**Abstract.** Using the Solar Isotope Spectrometer on the Advanced Composition Explorer, we have measured the heavy ( $Z \geq 6$ ) element abundances of 33 small solar energetic particle (SEP) events which occurred between 4 April, 1998 and 3 December, 2000. The events have been classified according to their elemental and isotopic composition as well as other defining characteristics. With the event-averaged heavy element fluxes, we have investigated the dependence of elemental abundances relative to those of the solar photosphere on first ionization potential (FIP). Where possible, we have examined the FIP fractionation effects on the average composition of the small SEP events, and discuss the ensuing implications for the origin and acceleration of nuclei in these events.

## 1 Introduction

Measurements of the elemental and isotopic composition of energetic nuclei from solar energetic particle (SEP) events can provide information about the acceleration mechanisms in these kinds of occurrences. SEP events have been classified into two main types: impulsive and gradual (Reames, 1995). During gradual events, which have a duration on the order of days, the abundances of heavy SEPs have been shown to vary according to their charge-to-mass ratio (Breneman and Stone, 1985). They are also characterized by depletions of a factor of  $\sim 4$  in elements with first ionization potential (FIP)  $> 10$  eV, relative to the photosphere (Breneman and Stone, 1985). The acceleration of the nuclei during these events is understood to occur at shock waves which are driven by coronal mass ejections (CMEs) (Gosling, 1993; Kahler, 1992, 1994; Reames, 1999). On average, the heavy element composition of SEP material from gradual events is expected to reflect that of the corona.

Impulsive SEP events commonly contain enhancements in Fe ( $\sim 10\times$ ) and in Ne, Mg, and Si ( $\sim 3\times$ ) relative to coronal abundances (Mason et al., 1986; Reames et al., 1994). Additionally, impulsive events typically have  $^3\text{He}/^4\text{He}$  ratios

which are up to 3–4 orders of magnitude larger than the solar wind value of 0.0004 (Gloeckler and Geiss, 1998). They are also understood to be associated with  $\sim\text{keV}$  electron emission from the Sun (Reames et al., 1985), as well as with X-ray flares, and typically last on the order of hours. It is not presently known whether SEP abundances from impulsive events have a dependence on FIP.

The observed differences between impulsive and gradual SEP events result from their distinct acceleration mechanisms. As stated above, gradual events are known to be associated with CME-driven shocks. However, while the  $^3\text{He}$  found in impulsive events may be selectively enhanced by ion cyclotron wave resonances (Fisk, 1978; Temerin and Roth, 1992) or by cascading Alfvén waves (Miller, 1998), the exact acceleration mechanism in impulsive events is not presently well understood. In this paper we have examined the heavy element content of 33 small SEP events. We have classified all but one of the events into three sub-groups according to their  $^3\text{He}$  content, and have compared their average elemental content with each other and with those of previous studies. We have also looked for a possible dependence of the SEP abundances on FIP during  $^3\text{He}$ -rich events.

## 2 Event Selection

The Solar Isotope Spectrometer (SIS) consists of a pair of silicon solid state detector telescopes which measure the energy loss ( $E$ ) and the rate of energy loss ( $dE/dx$ ) of incident energetic nuclei with  $10 \lesssim E \lesssim 100$  MeV/nucleon. Using these measured values of  $dE/dx$  and  $E$ , the charge and mass of the incident nuclei are derived through an iterative mathematical algorithm (Stone et al., 1998).

The 33 SEP events selected for this study were chosen according to three criteria. First, a set of 99 days between 4 April 1998 and 3 December 2000 were identified by requiring that the daily-averaged 11.0–26.5 MeV/nucleon Fe or 8.6–19.3 MeV/nucleon Mg fluxes be greater than a threshold of  $5 \times 10^{-7}$  particles/(s cm<sup>2</sup> sr MeV/nuc). Second, the days which overlapped with any of the known large, gradual SEP

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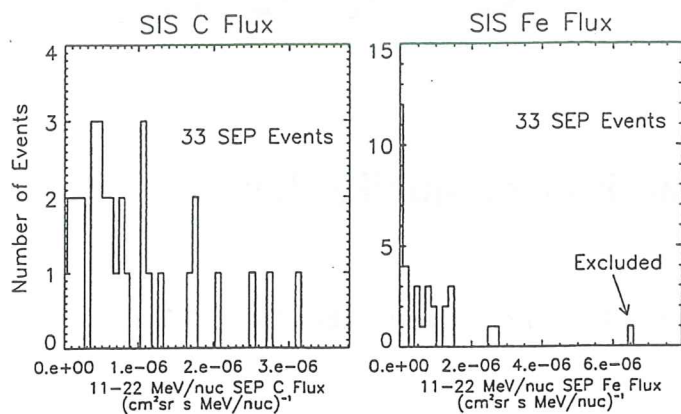


Fig. 1. SIS  $\sim 11$ –22 MeV/nucleon SEP C (left panel) and Fe (right panel) fluxes, with the low solar activity background fluxes subtracted, for the 33 SEP events in this study. The arrow in the right panel indicates the one SEP event which was excluded from the average heavy element abundance measurements reported in this study.

events were excluded from the study. Finally, the SIS  $\sim 3$ –5 MeV/nucleon He fluxes on the selected days were examined subjectively for well-defined SEP event onset times and terminations. The 33 events with well-defined onset times and terminations became the final data set examined in this study, while the days which did not show well-defined time profiles in the  $\sim 3$ –5 MeV/nucleon He flux were discarded. Even so, due to the frequent occurrence of this type of small SEP event, it is probable that some of the selected “good” events contain multiple injections from the same region on the Sun.

Of the 33 SEP events which passed the selection requirements described above, one event had much higher heavy element ( $Z > 6$ ) fluxes than the other 32 as shown in Figure 1. This event, which is atypical in size of the overall data set selected for this study, has been excluded from the average abundance measurements and analyzed separately in this paper. It took place on 1 May, 2000 (day 2000:122.3–123.0), and contained enhancements over coronal values in  $\sim 11$ –22 MeV/nucleon Fe/C of  $12.6 \pm 3.6$ , in Mg/C of  $5.1 \pm 1.6$ , and in Si/C of  $4.1 \pm 1.3$ . It occurred in coincidence with an M-Class X-ray flare and with a  $\sim 10$ –100 keV electron burst, which was measured using the Electron Proton and Alpha Monitor (EPAM) on ACE. It is not “ $^3\text{He}$ -rich” at  $\sim 4.5$ –5.5 MeV/nucleon energies according to the definition above ( $^3\text{He}/^4\text{He} = 4.7\%$ ). However, due to this event’s short duration, heavy element enhancements, and association with an electron burst and X-ray flare, we classify it as an “impulsive” SEP event.

The final set of 32 small events were subdivided into three groups according to their total  $\sim 4.5$ –5.5 MeV/nucleon  $^3\text{He}/^4\text{He}$  ratios. Of the 32 events, 17 had  $^3\text{He}/^4\text{He}$  ratios less than 0.065 (“ $^3\text{He}$ -poor” events), while 9 had  $^3\text{He}/^4\text{He}$  ratios which were between 0.065 and 0.1 (“moderately  $^3\text{He}$ -rich”). Finally, 6 of the events had  $^3\text{He}/^4\text{He}$  ratios greater than or equal to 0.1, and were designated “ $^3\text{He}$ -rich”. In general, the  $^3\text{He}$ -poor events had  $^3\text{He}/^4\text{He}$  ratios which were mea-

sured between 0.04 and 0.065. This apparent lower limit of 4% is probably due to spillover contamination of the  $^3\text{He}$  peak by the  $^4\text{He}$  peak. While the nomenclature “ $^3\text{He}$ -poor” may be misleading for these events, given that their  $^3\text{He}/^4\text{He}$  ratios are up to  $\sim 200\times$  that of the solar wind, we have chosen to use it as a convenient reference for the purposes of this study only.

While the unweighted average  $\sim 4.5$ –5.5 MeV/nucleon  $^3\text{He}/^4\text{He}$  ratio in the  $^3\text{He}$ -rich, moderately  $^3\text{He}$ -rich, and  $^3\text{He}$ -poor groups is  $\sim 20\%$ ,  $\sim 8\%$ , and  $\sim 5\%$  respectively, and impulsive events are expected to have higher  $^3\text{He}/^4\text{He}$  ratios than gradual events, it is not clear that our three event sub-groups are cleanly divided as such. For example, the unweighted average duration of the events in the  $^3\text{He}$ -rich ( $^3\text{He}$ -poor) subset is 2.1 (3.2) days, which is longer than expected for impulsive SEP events. This may be a result of contributions to the events by multiple injections from the same region on the Sun. Or, it could be that while the  $^3\text{He}$ -rich events contain a relatively large fraction of material which was originally accelerated in impulsive SEP events, they are not necessarily impulsive events. This idea stems from the suggestion by Mason et al. (1999), which says that residual material from past impulsive SEP events may provide a source population for further acceleration by CME-driven shocks associated with gradual events. Experimental observations of SEP composition during large gradual events (Cohen et al., 1999; Mason et al., 1999; Cohen et al., 2000; Wiedenbeck et al., 2000) and during times of low solar activity (Richardson et al., 1990; Slocum et al., 2001) have supported this idea.

### 3 Low Solar Activity Spectra

The contributions to the small SEP event spectra from galactic cosmic rays (GCR) and anomalous cosmic rays (ACR) have been estimated from SIS measurements during 241 days of low solar activity between 9 April, 1998 and 25 December, 2000. The 241 days were identified by examining the proton fluxes from the Electron, Proton, and Alpha Monitor (EPAM) instrument on board ACE, and requiring that the daily-averaged 1.06–4.75 MeV proton flux be less than  $0.16 \text{ (cm}^2 \text{ sr s MeV)}^{-1}$ . Next, the 241 days were grouped chronologically into three time periods of relatively constant solar modulation, based on inspection of SIS  $\sim 7$ –10 MeV/nucleon O fluxes. These time periods were 9 April, 1998–25 November, 1998, 26 November, 1998–14 January, 2000, and 15 January, 2000–25 December, 2000. For each of the three time periods, the average heavy element spectra were extracted from the daily measurements. These average heavy element spectra were weighted with the temporal fraction of the 32 small SEP events which occurred during each time period, and were subsequently summed for subtraction from the small SEP event spectra.

### 4 Heavy Element Measurements

Average energy spectra were measured for C, N, O, Ne, Na, Mg, Al, Si, S, Ca, and Fe for each of the three event sub-



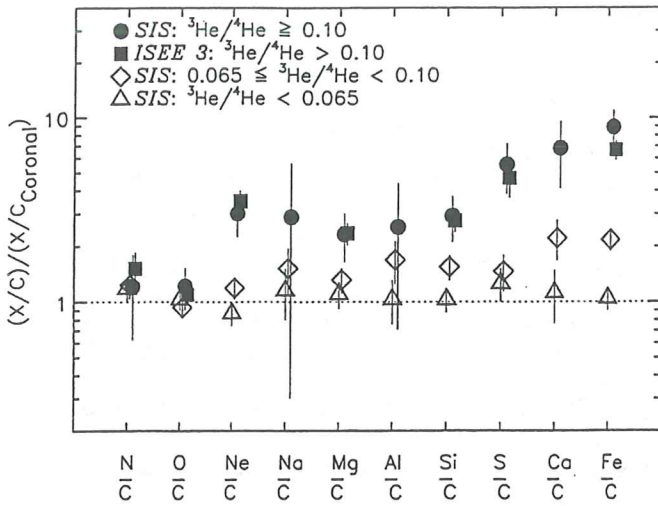


Fig. 2. Average abundances of ten heavy elements relative to carbon, normalized to coronal values (Reames, 1998), for the  $\sim 11$ –22 MeV/nucleon SIS data (filled circles, open diamonds, and open triangles), with cuts on the 4.5–5.5 MeV/nucleon  $^3\text{He}/^4\text{He}$  ratios as indicated. The filled squares denote the average abundances of seven heavy elements relative to carbon, measured using 1.9–2.8 MeV/nucleon ISEE 3 data (Reames et al., 1994) from a set of 228  $^3\text{He}$ -rich (1.3–1.6 MeV/nucleon  $^3\text{He}/^4\text{He} > 0.1$ ) events.

sets defined above. The spectra were calculated by summing the total number of counts in all events and dividing by the total amount of instrument livetime. Figure 2 depicts the  $\sim 11$ –22 MeV/nucleon relative abundances of ten heavy elements with respect to C, normalized to coronal abundances (Reames, 1998), for the  $^3\text{He}$ -rich, moderately  $^3\text{He}$ -rich, and  $^3\text{He}$ -poor SEP event subsets.

From Figure 2, it is apparent that while the composition of the  $^3\text{He}$ -poor data set generally reflects that of the corona, the moderately  $^3\text{He}$ -rich and  $^3\text{He}$ -rich SIS data sets contain enhancements relative to C in most measurable elements heavier than O. Also shown in the figure are the 1.9–2.8 MeV/nucleon abundances measured for a sample of 228  $^3\text{He}$ -rich (1.3–1.6 MeV/nucleon  $^3\text{He}/^4\text{He} > 0.1$ ) events from ISEE-3 (Reames et al., 1994). The SIS  $^3\text{He}$ -rich abundances are in very good agreement with the ISEE-3 data. In addition, since the coronal values chosen for normalization in this figure were derived from large gradual SEP events, it is likely that the  $^3\text{He}$ -poor events consist primarily of small “gradual” events.

The uncertainties shown in the plot include one standard deviation of statistical uncertainty as well as a 5% systematic contribution. They do not reflect any contribution from a possible non-statistical population spread in the event abundances. Because the events have not been analyzed individually, it is not possible to determine the magnitude of such an effect on the average uncertainties. Consequently, the error bars shown in Figure 2 may be an underestimation of the true uncertainties.

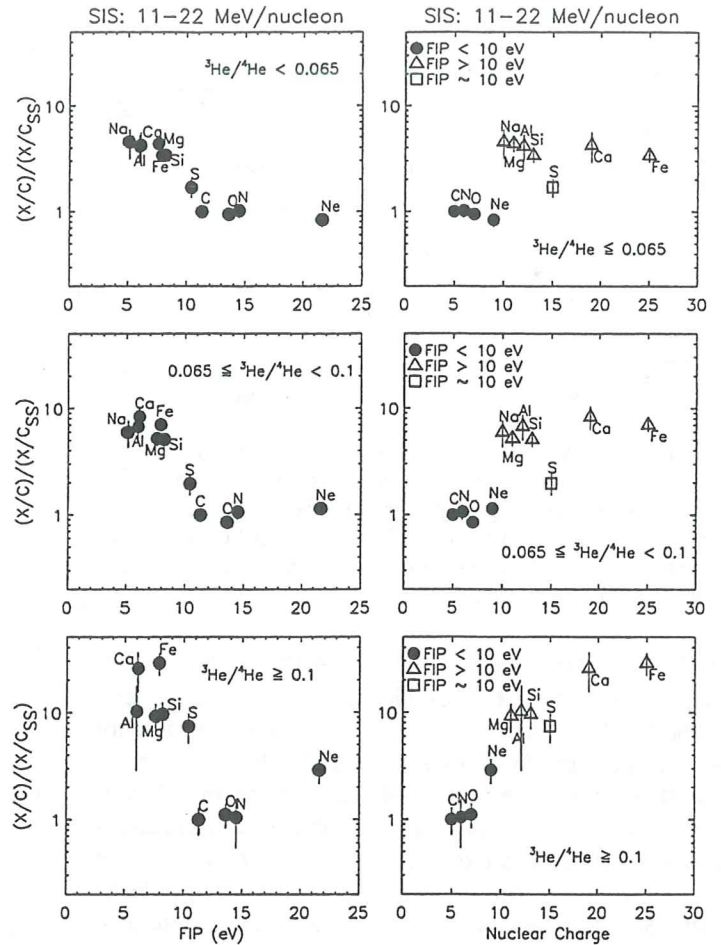


Fig. 3. Abundances relative to C, normalized to solar system values (Anders and Grevesse, 1989), plotted for all three event subsets against first ionization potential (FIP) (left panels) and against nuclear charge (right panels). The subset with the 17  $^3\text{He}$ -poor events are shown in the two top panels, the 9 moderately  $^3\text{He}$ -rich events are shown in the two middle panels, and the 6  $^3\text{He}$ -rich events are plotted in the two bottom panels. The error bars shown include one standard deviation of statistical uncertainty and a 5% systematic uncertainty.

## 5 First Ionization Potential

The heavy element abundances with respect to C in the three event subsets, normalized to solar system values (Anders and Grevesse, 1989), have been plotted against FIP and against nuclear charge in Figure 3. The top left panel, which depicts the average  $^3\text{He}$ -poor event heavy element content, shows a step of  $\sim 4$  between the abundances of the low-FIP ( $\text{FIP} < 10$  eV) and high-FIP ( $\text{FIP} > 10$  eV) elements. The average enhancement of the elements Al, Ca, Mg, and Si is  $4.0 \pm 0.5$ . This value is in agreement with the measured average value of the FIP step in gradual SEP events (Breneman and Stone, 1985).

The lower four panels in Figure 3 appear to be different than the top panels. The middle left panel, consisting of the average elemental abundances for the moderately  $^3\text{He}$ -rich subset of 9 events, has the qualitative appearance of a larger FIP step than that of the top panel. The average value of the enhancements of Al, Ca, Mg, and Si with respect to C, nor-



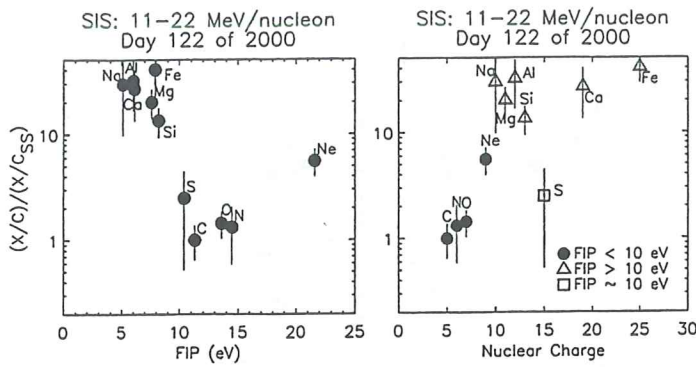


Fig. 4. Abundances relative to C, normalized to solar system values (Anders and Grevesse, 1989), plotted against FIP (left panel) and against nuclear charge (right panel) for the impulsive SEP event which occurred on 1 May, 2000 (Day 122.3–123.0 of 2000). The error bars shown include one standard deviation of statistical uncertainty and a 5% systematic uncertainty.

malized to solar system values, is  $6.2 \pm 0.7$ . Finally, the bottom panels with the 6  $^3\text{He}$ -rich events show enhancements in the low-FIP elements of  $\sim 10$ , with an average value for Al, Ca, Mg, and Si of  $14.8 \pm 3.6$ . The bottom right panel also shows a possible relationship between the ion enhancements and their nuclear charge, although S/C appears somewhat depleted on this plot. Similarly, it is important to note that the  $^3\text{He}$ -rich event subset shows enhancements in Fe/C, Ca/C, S/C, and Ne/C which are not necessarily attributable to a FIP-like effect.

As stated above, the impulsive SEP event which took place on 1 May, 2000 has been analyzed separately in a similar manner. Figure 4 shows the heavy element abundances of this event with respect to C, normalized to solar system values. In this event, there appear to be very large enhancements in the low-FIP elements. The average enhancement of Al/C, Ca/C, Mg/C, and Si/C over solar system values in this event is  $20.1 \pm 5.1$ . Also, similar to the  $^3\text{He}$ -rich data set in Figure 3, Fe/C and Ne/C show enhanced abundances which do not appear to be solely related to FIP.

The average heavy element abundances in the 32 smallest SEP events included in this study have shown increasing enhancements in the low-FIP elements with increasing  $^3\text{He}/^4\text{He}$  ratio. The larger impulsive event of 1 May, 2000 shows even greater enhancements in the heavy elements with low FIP, although the  $\sim 4.5$ – $5.5$  MeV/nucleon  $^3\text{He}/^4\text{He}$  ratio was only 4.7% in this event. Therefore, it is possible that FIP fractionation does affect the abundances of heavy elements in  $^3\text{He}$ -rich and impulsive SEP events. More data and investigation will be necessary to clarify this. However, if there is such an effect in these events, it is certainly not the only physical process which governs their SEP abundances.

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